Autonomous Oberving Strategies for the Ocean Carbon Cycle.

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Abstract:

Understanding the exchanges of carbon between the atmosphere and ocean and the fate of carbon delivered to the deep sea is fundamental to the evaluation of ocean carbon sequestration options. An additional key requirement is that sequestration must be verifiable and that environmental effects be monitored and minimized. These needs can be addressed by carbon system observations made from low-cost autonomous ocean-profiling floats and gliders.

We have developed a prototype ocean carbon system profiler based on the Sounding Oceanographic Lagrangian Observer (SOLO; Davis et al., 1999). The **SOLO/carbon** profiler will measure the two biomass components of the carbon system and their relationship to physical variables, such as upper ocean stratification and mixing. The autonomous observations within the upper 1500 m will be made on daily time scales for periods of months to seasons and will be carried out in biologically dynamic locations in the world's oceans that are difficult to access with ships (due to weather) or observe using remote sensing satellites (due to cloud cover). Such an observational capability not only will serve an important role in carbon sequestration research but will provide key observations of the global ocean's natural carbon cycle.

Keywords:

Autonomous, Ocean, Carbon, Remote, Sensing, Sequestration

1. Introduction.

The oceans contain approximately 50 times more carbon than the atmosphere and therefore can play an important role in carbon sequestration. About one-third of the carbon dioxide (2 of 6 Pg C y^{-1}; 1Pg = 10^{15} g) we emit is already being sequestered by the oceans. This uptake is largely driven by the increase of atmospheric CO_2 pressure due to emissions relative to the lower value the atmosphere would have if it were in equilibrium with the surface ocean. Once in the ocean, both movement of water masses and the ocean's "biological pump" act to move carbon into the deep sea; the biological pump moves carbon downward (across isopicnals) into the deep-sea but its operation is poorly understood. Models have shown that atmospheric CO_2 would rise by over 150 ppm without an operating biological pump (Siegenthaler and Sarmiento, 1993).

The Biological carbon Pump. Phytoplankton photosynthetically fix dissolved inorganic carbon (DIC) and nutrients to produce particulate organic carbon (POC), particulate inorganic carbon (PIC), and dissolved organic carbon (DOC). The term 'biological pump' (Fig. 1) describes the downward flow of fixed carbon (POC and PIC) from surface to deep waters. Fixed carbon is remineralized/dissolved/respired back to dissolved inorganic carbon at depth. The biological pump is 10-20% efficient at moving photosynthetically fixed carbon below 100 m, but only several percent efficient below 1000 m.

Although marine plant biomass equals approximately only 0.05% of terrestrial biomass, the amount of carbon processed is equal to that fixed by terrestrial plants (~50–100 Pg C/y). This seeming paradox is explained because marine plant biomass turns over on a time scale of hours to days, rather than seasons to years for terrestrial biomass. <u>This fact makes monitoring the variability of efficiency and linkages of the biological pump with depth a major oceanographic challenge.</u> Given the large amounts of carbon flowing through the biological pump on an annual basis, perturbations of the pump's transport efficiency could have a major impact on ocean carbon sequestration rates.

Major uncertainties in the ocean's carbon cycle are (1) how the biological pump responds to day to day variations in physical forcing, (2) the nature and quantity of

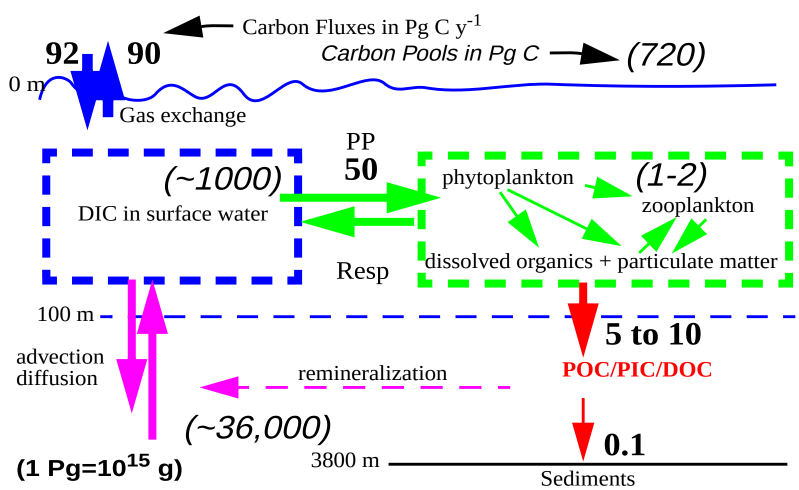

Fig. 1. Fluxes and pools of carbon in the ocean and a schematic of the biological pump.

carbon exported from the surface layer and the depth dependence of remineralization in the upper 1000 m, and (3) how this will change in the future.

2. Autonomous Floats and Gliders

An new armada of low-cost autonomous underwater vehicles is under development and will soon be able to perform key observations of the biological pump

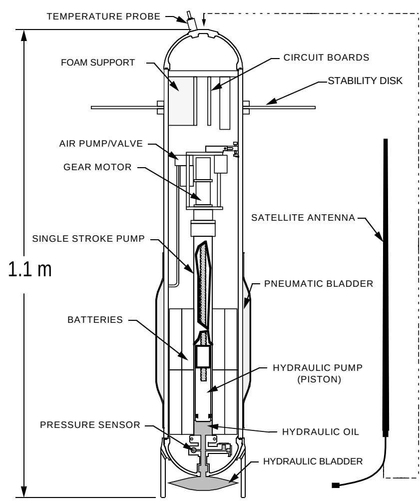

Fig. 2. Engineering schematic of SOLO (Davis et al., 1999). During operation SOLO drifts at mid-depth (ca. 1500 m), profiles to the surface for location, transmits profile data (depth, temperature, and salinity) via satellite telemetry, and then returns to depth. We will add sensors for POC and PIC concentration to SOLO. All profile data are available in near real time.

One attractive platform is the Sounding Oceanographic Lagrangian Observer (SOLO; Davis et al., 1999; Fig. 2). Over 1200 profiling lagrangian floats like SOLO have already been deployed in the oceans by the international physical oceanographic community. An international program named **Argo** is beginning to deploy 3000 more profiling floats for ocean climate studies (Wilson, 2000). SOLO operates by changing its buoyancy relative to surrounding water and has the power to make 100 plus round trips to the surface. Miniature submarine gliders, like the glider “Spray” being developed at Scripps and Woods Hole Oceanographic Institution (Sherman et al., 2000), have the ability to perform about 1000 round trips while navigating at 20 cm/sec. Such vehicles can operate in coastal waters or follow features in the open ocean waters and are designed to be recoverable.

3. Carbon System Sensors

Complete characterization of the ocean carbon system requires measurement of dissolved and particulate inorganic and organic carbon pools and fluxes (Fig. 3). For the purpose of demonstrating the concept of autonomous carbon system studies, we have chosen to demonstrate the measurement of the two components of carbon biomass: particulate organic carbon (POC) and particulate inorganic carbon (PIC). We choose POC and PIC measurement since the photosynthetic formation of POC and PIC have opposite effects on concentrations of dissolved CO_2 in seawater and low-power sensors are available for these quantities. Other investigators

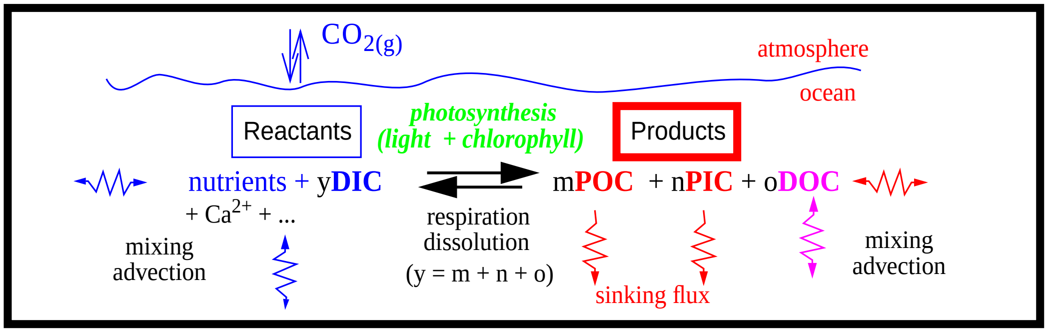

Fig. 3. Simplified representation of the transformations of the carbon system components in seawater. LBNL is developing **POC** and **PIC** **concentration** sensors. It is possible to develop optical strategies for assessment of the variability of the **POC** and **PIC** **flux**. Both developments would permit integration of two basic biogeochemical measurements with physical parameters routinely measured by floats, gliders and other autonomous ocean platforms now available.

are working to develop prototype sensors for reactant quantities like NO_3^-, Fe^{2+}, and components of DIC. Such sensors are being developed for mooring and surface drifter deployment and will be adapted to our platforms once their power requirements are reduced.

Remote in-situ sensing of POC and PIC concentration and flux. The optical detection of particulate organic carbon (POC) is based on the finding of a robust relationship between beam attenuation coefficient, ***c*,** measured by transmissometer and POC measured in samples obtained from the water column using in-situ filtration methods (Bishop, 1999; Bishop et al., 1999). Results showed that ***c*** and POC are highly correlated (r^2 >=0.95), with practically the same relationship (within a few percent) found over the wide range of ocean regions, depths and seasons sampled.

A PIC sensor is now under development at LBNL (Guay and Bishop, in preparation). Proof-of-concept experiments, using off the shelf optical components, have shown a highly-linear response to PIC concentration in the sensor. Preliminary results show that the sensor can operate over the entire oceanic concentration range and that the signal is not interfered with significantly by other particles.

We believe that it will be possible to adapt the optical principles used in the POC and PIC concentration sensors to measure POC and PIC fluxes in the near future.

4. Applications to Carbon Cycle Research:

In 2001 several of our **SOLO/carbon** profiling floats will be deployed in the north Pacific and Atlantic oceans to gather fundamentally new data on the temporal variability of carbon biomass and how biomass varies in response to day-to-day changes in the mixing and stratification of the upper ocean. The miniature submarine glider “Spray” will begin to perform surveys of the California current and gain information about the spatial variations of carbon biomass in relationship to ocean features seen in satellite remote sensing data. Both tests will demonstrate a new capability for autonomous carbon system observations in the ocean.

Evaluating Ocean Fertilization as a Carbon Sequestration Option. The viability of ocean fertilization as an ocean carbon sequestration option is dependent on the requirement to understand the impacts of large scale fertilization on the marine ecosystem and ocean biogeochemical cycles.

Recent experiments in the nutrient rich equatorial Pacific (IRONEX I, Martin et al., (1994); IRONEX II, Coale et al. (1996) and Southern Ocean (Southern Ocean Iron RElease Experiment; SOIREE, Boyd et al., (1999)) have demonstrated how easy it is to stimulate ocean productivity through iron fertilization of nutrient rich waters. Simply stated, adding one molecule of iron to an iron limited system permits the photosynthetic fixation of ~10^5 molecules of carbon (Martin and Fitzwater 1988, Martin et al., 1992). The fate of the extra organic matter produced is still not understood due to the short duration of fertilization experiments.

Unexpected results were found during a fertilization experiment in the southern ocean. Boyd et al. (1999) added 3800 kg of Fe (as $FeSO_4$) to a 50 km^2 area of the southern ocean near 61 S 141 E from 10 to 23 Feb. 1999. By the time the ship left the area on February 28, the patch had elongated to 150 km^2 and chlorophyll had increased 6 fold and air-sea pCO_2 difference decreased by 30 μatm compared with surrounding waters (Watson et al., submitted). Contrary to expectations, there was no measurable increase in particulate organic matter export from the patch during the 18 day period of observation (Charrette and Buesseler; 1999). This led Bakker et al. (1999) to conclude that all the organic matter formed was retained in surface waters. Not only was the patch persistent 4 weeks after the experiment, but SOIREE scientists believe they identified the fertilized area in satellite imagery a full 7 weeks after the ship departed the area. This clearly was contrary to expectations that the ocean would return to its ‘natural’ state by mid-March 1999 (NIWA press release 1999). Lagrangian profiling floats and gliders adapted to measure carbon concentrations and fluxes will be able to provide information on the fate of carbon sequestered by such experiments long after the experiment has occurred.

Evaluating Direct CO_2 Injection as a Carbon Sequestration Option. Introducing concentrated streams of CO_2 directly into the deep-sea avoids many of the biological and geochemical effects that may occur during ocean fertilization sequestration efforts. Never-the-less organisms are impacted by pH changes and elevated levels of CO_2 near to the site of injection. Self-navigated gliders like Spray can provide environmental information on plume dispersion 100’s of m to 10’s of km away from the site of introduction.

5. Summary

The combination of autonomous platforms and sensors described above opens up exciting new capabilities for carbon cycle observations to be made in the global oceans. The technologies do not replace observations that must be made from oceanographic platforms such as research vessels, deep-sea moorings, and surface drifters; however they do enable low-cost high-precision determination of basic carbon system parameters within the upper 1500 m on daily time scales for periods of months to seasons. Autonomous floats and gliders can operate in biologically dynamic locations in the world's oceans and during seasons that are difficult to study any other way. Such a new observational capability not only will serve an important role in carbon sequestration research but will provide key observations of the global ocean's natural carbon cycle.

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